Direct and indirect effects of rainfall and vegetation coverage on runoff, soil loss, and nutrient loss in a semi-humid climate

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Abstract: Soil and nutrient loss play a vital role in eutrophication of water bodies. Several simulated rainfall experiments have been conducted to investigate the effects of a single controlling factor on soil and nutrient loss. However, the role of precipitation and vegetation coverage in quantifying soil and nutrient loss is still unclear. We monitored runoff, soil loss, and soil nutrient loss under natural rainfall conditions from 2004 to 2015 for 50-100 m^2 runoff plots around Beijing. Soil erosion was significantly reduced when vegetation coverage reached 20 and 60%. At levels below 30%, nutrient loss did not differ among different vegetation cover levels. Minimum soil N and P losses were observed at cover levels above 60%. Irrespective of the management measure, soil nutrient losses were higher at high-intensity rainfall (Imax30>15 mm/h) events compared to low-intensity events ($p < 0.05$). We applied structural equation modelling (SEM) to systematically analyze the relative effects of rainfall characteristics and environmental factors on runoff, soil loss, and soil nutrient loss. At high-intensity rainfall events, neither vegetation cover nor antecedent soil moisture content (ASMC) affected runoff and soil loss. After log-transformation, soil nutrient loss was significantly linearly correlated with runoff and soil loss ($p < 0.01$). In addition, we identified the direct and indirect relationships among the influencing factors of soil nutrient loss on runoff plots and constructed a structural diagram of these relationships. The factors positively impacting soil nutrient loss were runoff (44-48%), maximum rainfall intensity over a 30-min period (18-29%), rainfall depth (20-27%), and soil loss (10-14%). Studying the effects of rainfall and vegetation coverage factors on runoff, soil loss, and nutrient loss can improve our understanding of the underlying mechanism of slope non-point source pollution.

1. Introduction

On a global level, soil erosion is a widespread phenomenon and has become a serious environmental problem in various ecosystems (Fu et al., 2011; Wuepper et al., 2019; Alewell et al., 2020). Surface runoff and soil loss cause soil nutrient loss, resulting in decreased soil fertility (Adimassu et al., 2014; Shi et al., 2018) and in the eutrophication of water bodies, which seriously threatens land productivity and water quality (Guo et al., 2010; Napoli et al., 2017; Shi et al., 2018). Rainfall strongly affects runoff, sediment, and nutrient loss (Ferreira et al., 2018), and soil nutrients are partially attached to soil particles and partially dissolved in water and lost by runoff (Kato et al., 2009; Shi et al., 2018). Runoff, soil erosion, and soil nutrient loss are complex processes controlled by various factors (Guo et al., 2010), such as precipitation, soil physical and chemical properties, soil moisture content, vegetation cover, and tillage measures (An et al., 2013; Kurothe et al., 2014; Mutema et al., 2015; Patricio et al., 2016). Various models have been constructed to calculate and predict soil nutrient losses (Shi et al., 2018; Zhou et al., 2019).

Rainfall and runoff are the main factors driving soil nutrient loss (Cantón et al., 2011; Jung et al., 2015), and about 70% of rainfall is converted to runoff in summer chemical fallow (Daniel et al., 2006; Liu et al., 2016); Hydrological changes are generally caused by altered rainfall patterns and have a significant impact on soil nutrient loss. Climate change and different climate patterns are associated with regional variations in extreme rainfall events (Nearing et al., 2004; Ohba and Sugimoto, 2019; Duan et al., 2020).The contribution of extreme rainfall events to runoff and sediment yield is much greater than that of ordinary rainfall events in red soil areas of South China, but land management can effectively reduce slope runoff and sediment yield (Duan et al., 2020). Studies have shown that soil erosion responds linearly to extreme precipitation events (Thothong et al., 2011). soil erosion and soil nutrient loss caused by runoff are significantly correlated with accumulated rainfall and rainfall erosion rate (Jung et al., 2015; Napoli et al., 2017; M. C. Ramos et al., 2006). Based on previous studies, rainfall intensity is an important driving force for soil transport (Qin et al., 2010; Wang et al., 2015), and therefore, the consideration of runoff in the general soil loss equation will improve the predictive power of the model (Kinnell, 2014).

The vegetation cover is the main environmental factor affecting runoff and soil erosion (Zhao et al., 2013), and the canopy can trap 10-20% of rainfall (Ghimire et al., 2012; Kurothe et al., 2014; Rungee et al., 2019; Nazarbakhsh et al., 2020). Previous studies have shown that the runoff with low coverage has the greatest correlation with soil erosion, indicating that with the increase in coverage, soil erosion decreases (Gaal et al., 2014; Marques et al., 2008). Based on long-term hydrological observations, vegetation restoration and afforestation result in a decrease in runoff, thereby reducing sediment yield and soil nutrient loss (Molina et al., 2012). The root system also has a significant effect on hydrology. On the one hand, the macropores formed by the root system create the conditions for the preferential flow, while on the other hand, aboveground vegetation increases surface roughness and reduces surface scouring by runoff (Kurothe et al., 2014). In addition, vegetation can also improve the soil texture (Fattet et al., 2011).

An antecedent soil moisture content is related to vegetation and hydrology, and the soil water status changes with soil nutrient loss via alterations in soil seepage (Fattet et al., 2011). Vegetation can improve soil conditions by adjusting evapotranspiration and soil wetness; it also absorbs soil water to reduce soil water storage. A previous study has determined the optimal vegetation coverage by modelling the relationship between soil water consumption and plant growth (Fu et al., 2012).

Most studies on the relationship between vegetation and soil erosion were based on indoor simulated rainfall experiments with various degrees of vegetation disturbance, resulting in a certain impact on the results. Rainfall intensity in control experiments is considered as a taxonomic variable, and soil erosion under natural rainfall cannot be adequately characterized. Although the effects of rainfall and environmental factors on runoff and soil loss have been extensively studied, research on the complex interactions between various factors and the quantification of their influence is still scarce (Wang et al., 2015; Zhou et al., 2016). More advanced methods are needed to determine the direct and indirect relationships between such factors and soil nutrient loss. The structural equation model identifies the direct, indirect, and total effects of the influence of the independent variable on the dependent variable via statistical analysis. It has been used to solve complex environmental problems, while few studies have applied this method to soil nutrient loss (Chamizo et al., 2012; Rodríguez-Caballero et al., 2013; Taka et al., 2016). In this sense, we assumed that: (1) There are thresholds for vegetation cover to control soil erosion and nutrient loss; (2) factors such as rainfall and vegetation cover jointly drive soil erosion and nutrient loss. This study takes slope runoff under natural rainfall events as the research object, quantifies the impact of vegetation on runoff sediment and nutrient loss through a large number of monitoring data, and uses the structural equation model to quantitatively analyze the direct and indirect impacts of rainfall and environmental factors on slope runoff and erosion. Finally, the vegetation coverage threshold interval of soil erosion and nutrient loss was determined to provide a basis for optimizing the decision making in soil erosion and nutrient loss management.

2. Materials and Methods

2.1 Study site

The runoff plots in this study were distributed in various districts of Beijing (115.7°E-117.4°E , 39.4°N-41.6°N), with a continental monsoon climate. Fig. 1 shows the locations of runoff plots across China. Average annual precipitation is 600 mm, and the rainy season lasts from June to August, accounting for 70% of the annual precipitation. The predominant soil is Luvisol

(USDA soil taxonomy), which is the main soil type in Beijing. We sampled 31 runoff plots with a size of 10×5 m and 20×5 m and studied the influence of vegetation coverage on runoff, sediment, and nutrient loss. To effectively control variables, we only selected nine runoff plots in Danli, Beijing. All rainfall events were simultaneously measured on all nine plots. The microtopography of these plots was flat, vegetation mainly consisted of a deciduous shrub (*Vitex negundo L. var. heterophylla (Franch.) Rehd.*) and white grass (*Pennisetum centrasiaticum Tzvel.*), and vegetation coverage ranged from 5 to 90%.

2.2 Response variables and explanatory variables

Data were collected from the Beijing Soil and Water Conservation Station and the China Academy of Water Resources and Hydropower Research. An automatic monitoring system for runoff plots and soil and water conservation was established in Beijing. Runoff from rainfall was collected by runoff buckets and monitored automatically via a water level gauge. When rainfall occurred, intensive water level measurements were taken every 2 min. After each rainfall event, the mixed water samples in the runoff bucket were collected, and the sediment and nutrient contents in the water samples were determined in the laboratory. Our dataset contained all rainfall events recorded from 2004 to 2015 in the experimental sites. Owing to an instrument malfunction, some of the rainfall field data were negative and blank, and the number of error data was below 1%; these data were therefore excluded from analysis. A total of 997 natural rainfall events were collected from runoff plots. The monitored variables runoff (RO: m^3/km^2), soil loss (SL: t/km^2), soil nutrient loss (nitrogen (N: kg/km^2); phosphorus (P: kg/km^2), and chemical oxygen demand (COD: kg/km^2) were used as response variables. The plot types were as follows: Grassland (GL); Farmland (FL); Horizontal bar (HB); Terranes (TR); Fish scale pit plot (SH). Precipitation and environmental factors considerably influence hydrological responses, and thus, the variables rainfall duration, maximum rainfall intensity over a 30-min period (Imax30), rainfall depth, vegetation coverage, rainfall erosivity (R_e), and antecedent soil moisture content (ASMC) were used to explain variation in runoff, soil loss, and soil nutrient loss.

Owing to the lack of rainfall data, the regression equation of rainfall erosivity applicable to the Beijing area was used:

$$R_e = 0.2463 \times P_r \times Imax30$$

where R_e is rainfall erosivity, MJ·mm/(hm^2·h); P_r is rainfall depth, mm; and Imax 30 is maximum rainfall intensity over a 30-min period, mm/h.

Table 1 shows the mean characteristics of all groups. The K-mean clustering divides the dataset into high-intensity events (n = 267), with an average value (Imax30) of 22.61 mm/h, ranging from 15 to 40 mm/h, and low-intensity events (n = 730), with an average value (Imax30) of 6.86 mm/h, ranging from 0.1 to 14.7 mm/h. The high-intensity events produced a rainfall depth about twice as high as the low-intensity events.

2.3 Statistical analysis

We used the structural equation model (SEM) to quantify the direct and indirect effects of explanatory variables on response variables. Given the complex relationship between hydrological and environmental factors and possible influence of plant coverage on runoff, soil loss, and nutrient loss, we used SEM to test the correlation. To improve data normality, data were square root- and log-transformed. First, the correlation matrix between variables was calculated to explore the correlation between explanatory variables and response variables. Subsequently, a priori hypothesis model was established according to previous knowledge (Fig. 2), and unsupervised K-mean classification was employed to partition rainfall into high-intensity and low-intensity events based on the Imax30. There were 267 high-intensity rainfall events and 730 low-intensity rainfall events. Individual path coefficients between variables were assessed by the multivariate Wald test ($p < 0.05$), and non-significant paths and variables were removed from the model to reduce model complexity. Modification indices can be used to increase the path in order to reduce the chi-square value of the model and to obtain an acceptable model.

Six model fit indices were used to test the goodness of fit of model: (i) p value, (ii) χ^2/ df: the quotient of the Chi square and the degrees of freedom, (iii) RMSEA: root mean square error of approximation, (iv) CFI: comparative fit index, (vi) NFI: the non-normed fit index, (vii) IFI: incremental fit index. The value range of indicators with good model fitting is listed in Table 1. Standardized path coefficients were estimated using generalized least squares analysis. The SEMs were developed and tested with the SPSS AMOS 18 software (AMOS Development Corp., Mount Pleasant, South Carolina, USA).

3. Results

3.1 Effects of vegetation cover on runoff, soil loss, and nutrient loss

Fig. 3 shows the runoff, soil loss, and soil nutrient loss in plots under different vegetation coverage levels. With the increase in vegetation coverage, runoff and soil loss were significantly reduced (Fig. 3a, b). When vegetation coverage was higher than 60%, runoff and sediment decreased with increasing vegetation cover, but the difference was not significant. However, soil nutrient loss did not increase significantly with increasing vegetation coverage. At 90% vegetation coverage, soil P loss was greater than at 60%. When vegetation coverage was below 30%, the difference in soil nutrient loss among different vegetation cover levels was not significant. At a vegetation coverage level of 60%, soil N and P losses were minimal (Fig. 3c).

3.2 Soil nutrient loss characteristics under different rainfall intensities

Fig. 4 shows the effect of soil management on soil nutrient loss under different rainfall patterns. Significant differences were observed for soil nutrient loss between high-intensity and low-intensity rainfall events. Under all management measures, soil nutrient loss at high-intensity rainfall events was generally higher than at low-intensity rainfall events ($p < 0.05$). Regarding the different management measures, soil nutrient loss followed the order FL > TR > GL > HB > SH. The reduction rates of soil P loss caused by low-intensity rainfall under different land management measures were as follows: SH (83.82%) > HB (81.34%) > TR (65.12%) > FL (57.79%) > GL (23.19%). The reduction rates of soil N loss caused by low-intensity rainfall events were as follows: TR (79.53%) > FL (57.79%) > HB (53.18%) > SH (51.77%) > GL (47.07%). The COD reduction rate followed the order TR (78.67%) > SH (70.41%) > HB (68.47%) > FL (62.25%) > GL (50.49%).

3.3 SEM of high-intensity and low-intensity rainfall events

The high-intensity and low-intensity rainfall structural equation model is presented in Fig. 5. The final models showed good fit, with CFI, NFI, and IFI over 0.9 and $p > 0.05$ (Table 2). In the low-intensity model, 29 and 15% of variance in runoff and soil loss, respectively, were explained (Fig. 5a). Rainfall duration had the strongest influence on rainfall depth (path coefficient = 0.52), while rainfall depth had a strong effect on runoff (path coefficient = 0.44). Rainfall duration had a direct negative effect on RO (path coefficient = -0.16) and an indirect positive effect on RO because of its positive causal effect on rainfall depth (path coefficient = 0.52). Imax30 had a direct (0.22) and indirect (0.45) positive effect on RO and a direct effect on SL (path coefficient = 0.06).

Rainfall duration and vegetation coverage had a direct negative influence on soil loss (path coefficient = -0.26 and -0.13). Rainfall erosivity had a strong direct positive effect on SL (path coefficient=0.51).

For high-intensity rainfall events, there were no effects of vegetation and ASMC on runoff and soil erosion (Fig.5b), most likely because the effect of these factors is masked by the intensity of rainfall. Therefore, they were removed from the model to improve the fit. In the high-intensity rainfall model, 32 and 3% of variance in runoff and soil loss, respectively, were explained (Fig. 5b). Neither rainfall duration nor Imax30 had a significant causal effect on soil loss. The variation in runoff and soil loss was 32 and 3%, respectively, and R_e had a direct positive effect on SL (path coefficient =0.25). Compared with low-intensity rainfall events (path coefficient=0.22), the Imax 30 of high-intensity rainfall events had a greater influence on R_e (path coefficient=0.43).

3.4 Relationship between runoff, soil loss, and soil nutrient loss.

We found low to high correlations between response variables and explanatory variables (Table 4). The largest correlation coefficients were observed between RO and N and COD as well as between N and COD. Imax30 and rainfall depth had positive effects on runoff, soil loss, and soil nutrient loss. However, ASMC and vegetation coverage were negatively correlated with RO, SL, and nutrient loss, while Imax30 and RO and soil nutrient loss showed moderate correlations (R = 0.27-0.35). Moderate correlations (R = 0.31 and 0.33) were also observed between depth and nutrient loss. The SL was only slightly significantly correlated with RO and soil nutrient loss (R = 0.11-0.19, $p < 0.01$), while ASMC was negatively and significantly correlated with N and COD loss (R = 0.16 and 0.15, $p < 0.01$). In terms of explanatory variables, Re was significantly correlated with SL and soil nutrient loss (R = 0.114-0.439, $p < 0.01$), indicating that Re considerably contributed to soil erosion and nutrient loss. This is consistent with the results of Napoli et al. (2017). In addition to extreme precipitation events, high intensity precipitation events also contributed significantly to the annual erosion rate (Ramos and Martínez−Casasnovas, 2009).

Nutrient loss increased linearly with runoff and soil loss after logarithmic transformation (Fig. 6). The correlation between soil nutrient loss and runoff (R^2= 0.51-0.64) was higher than that between soil loss (R^2= 0.42-0.48). We used the stepwise multiple linear regression model to assess the correlation between soil nutrient loss and explanatory variables (Table 3). For soil nutrient loss, RO was considered the largest variable; the factors RO, ASMC, and SL had the greatest ability to predict soil N loss and explained 63.2% of the variability.

3.5 Soil nutrient loss SEM model

The revised SEM describes the effects of rainfall and environments factors on soil nutrient loss (Fig. 7). Similar relationships among response variables and explanatory variables were found for soil N, P, and COD loss. Among all explanatory variables, rainfall factors had the strongest direct influence on soil nutrient loss. While Imax30 had a direct positive effect on SL, it had an indirect positive effect on soil nutrient loss because SL had a direct positive influence on soil nutrient loss Moreover, environmental factors had a moderate influence on soil nutrient loss. Of these, runoff had the strongest influence on SL and nutrient loss. The path coefficients (0.50-0.64) indicate that runoff was the most important driving force of soil nutrient loss. In addition to soil N loss in the SEM model, rainfall duration only slightly negatively influenced soil P and COD loss (path coefficient = 0.11 and 0.05). The variance explained for soil P loss was 55%, while it was slightly lower for soil N (63%) and COD (67%) loss. Vegetation coverage directly negatively affected SL (path coefficient = -0.11). Re directly positive affected soil nutrient loss (path coefficient=0.08-0.1).

The direct, indirect, and total effects of environmental factors, precipitation, and hydrological factors on soil nutrient loss are shown in Fig. 8. Soil nutrient loss was directly affected by RO (56-74%), followed by SL (16-23%). However, Imax30 and rainfall depth had the largest indirect effects on soil nutrient loss, ranging from 47-50% and from 31-34%, respectively. Rainfall duration had a direct negative effect on soil nutrient loss (6-12%). Overall, the factors positively impacting soil nutrient loss followed the order RO (35-38%), Imax30 (27-29%) and depth (17-19%), and SL (7-11%).

4. Discussion

4.1 Rainfall intensity

Precipitation is the main factor driving runoff and soil loss. Soil erosion is not only driven by extreme precipitation, but also by short precipitation events with low rainfall intensity (Ramos et al., 2009). Under natural conditions, rainfall events show a skewed distribution (skewness=2.79). Although strong storm events account for a small percentage of all precipitation events, they exert most of the erosion throughout the year (Ramos et al., 2004; Ziadat & Taimeh, 2013). In high-intensity rainfall events, there was no negative correlation between Imax30 and rainfall duration (Fig. 5b). Natural rain patterns are mostly short duration of high intensity rainfall and long duration of low intensity rainfall. In this study, high-intensity rainfall events, classified by K-means clustering, accounted for 26.8% of all precipitation events. In low-intensity rainfall events, vegetation coverage negatively affected soil loss (Fig. 5a). Nevertheless, the negative relationship between vegetation cover and soil loss disappeared with high-intensity rainfall, suggesting that the effect of the vegetation cover on soil loss could be overridden by rainfall intensity. In high-intensity rainfall, Imax30 had an indirect effect on soil loss, while in low-intensity events, this effect was direct (Fig. 5). This phenomenon was consistent with previous results (Rodríguez et al., 2014). The Imax30 directly affected soil loss in low-intensity rainfall events, which was not the case in high-intensity rainfall events. One possible reason for this interesting phenomenon is that intense rainfall can quickly form a thin film water film, preventing the raindrops from hitting the ground directly. In low-intensity rainfall events, raindrops hit the surface directly and mix the disturbed soil particles with runoff (Wang et al., 2017).

There are two mechanisms of runoff production in semi-arid and semi-humid areas: surface saturation and infiltration excess, which do not occur independently. Previous studies have shown that the production of rainfall depth and rainfall intensity is well correlated with runoff (Mayor et al., 2011; Mayor et al., 2007), mainly because rainfall depth can well predict runoff in semi-arid and semi-humid areas, while rainfall intensity adequately predicts runoff in humid areas. According to the structural equation model, runoff was directly affected by both rainfall depth and intensity, indicating that the runoff mechanism is the result of surface saturation and infiltration excess. Compared with low-intensity rainfall, the path coefficient of rainfall intensity on runoff in high-intensity rainfall events increases, while the path coefficient of rainfall depth on runoff decreases (Fig. 5), indicating that the dominant role of infiltration excess was greater under high-intensity rainfall events (Rodríguez-Caballero et al., 2014).

4.2 Vegetation coverage

Based on our results, runoff and sediment losses significantly decreased with increasing vegetation coverage (Fig. 3). Regarding soil nutrient loss, the influence of vegetation coverage between 5 and 30% on soil nutrient loss was not significant. There was no significant difference in soil P loss for vegetation cover levels between 20 and 90%. When vegetation cover was 60%, soil N and P losses were lowest (Fig. 3). Vegetation coverage has a nonlinear threshold effect on soil erosion (Jiang et al., 2019). Previous studies have given different thresholds for the effects of vegetation on sediment reduction, which are related to local climatic conditions (Martínez-Zavala et al., 2008; Moreno-de Las Heras et al., 2009; Liu et al., 2018; Chen et al., 2019;). Liu et al. (2018) divided the vegetation coverage threshold into two parts; when vegetation coverage reaches a low threshold (30%), vegetation can effectively reduce soil and water loss, and when it reaches a high threshold (50%-60%), vegetation increases soil erosion. This is consistent with the results of this study. With increasing vegetation coverage, the water retention ability of the root system increases. However, with increasing levels of vegetation litter, soil nutrient levels with also greatly increase (Brazier, Turnbull, Wainwright, & Bol, 2014). At the same time, the increased root system improves the physical and chemical properties of the surrounding soil (Gao et al., 2009). Vegetation type can affect soil nutrient loss in the basin (Hervé−Fernandez et al., 2016). Turnbull et al. (2011) studied the loss and redistribution of soil N and P caused by runoff in the process of grassland degradation to shrub land and found that in areas dominated by shrubs, N losses were considerably higher than in grass areas. Also, runoff levels decreased with increasing vegetation cover. However, Michaelides et al. (2009) found that the runoff did not seem to change significantly when the vegetation changed to shrub-dominated on the plot scale, but due to the differences in slope and soil type, erosion patterns may vary.

Vegetation plays an important role in the vertical water balance of precipitation, and a negative effect of vegetation cover on soil erosion was found in the structural equation model. Vegetation consumes soil moisture through evapotranspiration, especially during the growing season (Rungee et al., 2019; Nazarbakhsh et al., 2020). On the one hand, the canopy can intercept rainfall and reduce the impact of raindrops on the ground (Ghimire et al., 2012), while on the other hand, the large pores formed by the roots can also increase infiltration and reduce runoff and soil loss (Kurothe et al., 2014; Liu et al., 2016). Previous studies have found that soil erosion is more sensitive to changes in vegetation than runoff (El Kateb et al., 2013; M.A.Nearing et al., 2005). The threshold of rainfall runoff was positively correlated with vegetation coverage. In a previous study, when vegetation cover exceeded 65%, runoff reduction was significantly improved (Descheemaeker et al., 2006). A high vegetation coverage leads to the loss of rainfall and the reduction of kinetic energy, which has a negative effect on soil erosion.

4.3 Relationship between runoff, soil loss, and soil nutrient loss

In this study, soil nutrient loss was more correlated with runoff than soil erosion (Fig. 6). Previous studies have shown that soil erodibility significantly affects sediment-related nutrient loss and presents a positive logarithmic relationship (Wang et al., 2014; Cheng et al., 2018). Based on a previous study, sediment-associated nutrient loss accounts for 77% of the total soil nutrient loss (Cheng et al., 2018). Frequent low-intensity rainfall, which carries nutrient-rich soil particles, poses a greater threat to soil nutrient loss (Norton et al., 2007; Girmay et al., 2009). In addition, erosion-related nutrient loss is also related to slope, soil moisture content, rainfall intensity, vegetation coverage, and land use patterns (Girmay et al., 2009; Zhang et al., 2011; Xing et al., 2016; Cheng et al., 2018). In our study, the stepwise multiple linear regression equation shows that runoff was the important predictor of soil nutrient loss, explaining 35.5, 61.9, and 56.4% of soil P, N, and COD loss, respectively (Table 3). The SEM results of direct effects were similar to those of the stepwise multiple linear models. After adding other factors, the predictive power of the equation was slightly improved (Table 3). A study by Girmay et al. (2009) found that the prediction ability of the model can be improved by 16% with the addition of the vegetation cover (Girmay et al., 2009). Compared with rainfall, plot variables account for poor hydrological variability, and such poor explanation can be attributed to several factors: (1) The vegetation and topographic conditions of plots are single; (2) the influence factors are not all included, such as slope, litter, and biological soil crusts. The multiple linear regression equation shows that antecedent soil water content had negative effects on soil N and COD loss (Table 3), most likely because nitrogen and phosphorus show different forms during runoff erosion. In general, phosphorus tends to adhere to soil particles and is lost with soil erosion, while most nitrogen is soluble and moves with runoff (Lu et al., 2016).

4.4 Direct and indirect effects of explanatory factors on response variables

Antecedent soil water content is closely related to runoff mechanisms. In semi-arid and semi-humid areas, rainfall reaching the surface mainly forms runoff by surface saturation. However, in humid areas, infiltration excess is the dominant runoff mechanism. In the structural equation model, antecedent soil water content had a negative effect (Fig. 7). Soil erodibility is closely related to soil type, soil structure, and soil moisture content. Cheng et al. (2018), studying the effect of soil moisture content on erosion, found that soil loss increased with soil moisture content in areas with a high-water content, but decreased in areas with a low content. The higher the soil moisture content, the more conductive it is to the formation of surface runoff and soil nutrient loss. When soil saturation leads to surface runoff, the protective effect of runoff will weaken the splash of raindrops, and the stability of soil aggregates will change, making soil particles more easily separated by runoff (Michaelides et al., 2009; Hu et al., 2018; Neris et al., 2013).

We found negative effects of rainfall depth and runoff on soil moisture content. Higher amounts of rain are lost in the form of runoff, and only a small amount seeps into the soil to replenish soil moisture. Atmospheric evaporation and the time interval of the last precipitation are the main factors determining the soil moisture content. Using the structural equation model, we did not find a direct effect of soil moisture on soil nutrient loss. However, based on a series of simulated rainfall experiments, Cheng et al. (2018) observed that the soil nutrient loss associated with runoff was highest at a soil moisture content of 30%. Most likely, this is because soil surface nutrients quickly dissolve and are lost with runoff when the soil moisture content is high. However, at low soil moisture levels, a high soil infiltration rate leads to the delay in runoff formation time, and soil nutrient loss is caused by rainwater infiltration into the soil (Cheng et al., 2018).

4.5 Scale effect and outlook

The scale effect represents an important issue in eco-hydrology. This study quantified the interaction between the influencing factors and the contribution rate of erosion at the plot scale. Owing to the single conditions of vegetation, soil, and topography, the results cannot be directly extended to the watershed scale. The conclusions of this study are helpful to understand the formation mechanism of soil erosion and nutrient loss at the slope scale. There is a threshold interval between vegetation and soil loss, and vegetation coverage can be divided into three threshold areas: lower threshold (0-20%), medium threshold (20-60%), and upper threshold (60-100%). Therefore, a vegetation coverage of 20% can be defined as an erosion warning line, and vegetation should be mainly restored manually. When the vegetation coverage is more than 60%, natural restoration is recommended as the main vegetation restoration pathway. This study provides a restoration strategy for vegetation cover of soil erosion and nutrient loss at the slope scale in the subhumid climate region of northern China, providing a scientific basis for decision makers.5. Conclusions

We systematically analyzed the interactive effects of natural rainfall and environmental factors on runoff, soil, and nutrient loss at the plot scale. Soil erosion is significantly reduced when vegetation coverage reaches 20 to 60%. At levels below 30%, the difference in soil nutrient loss under different vegetation cover levels is not significant. When vegetation cover is 60%, N and P losses are minimal. Irrespective of the land use type, soil nutrient loss at high-intensity rainfall events was higher than at low-intensity rainfall events ($p < 0.05$). The structural equation model can reveal more information on the effects of rainfall characteristics and environmental factors on hydrological responses. Rainfall duration is still the key factor affecting rain accumulation. In high-intensity rainfall events, we found no causal relationship between vegetation cover, antecedent soil moisture content, and hydrological responses. After logarithmic transformation, soil nutrient loss was significantly linearly correlated with runoff and soil loss, and runoff was the most important predictor of soil nutrient loss. In the structural equation model of soil nutrient loss, vegetation cover and soil moisture content negatively affected soil loss. The variance explained for soil P, N, and COD was 55, 63, and 67%, respectively. We established the relationship structure of the direct and indirect effects of rainfall characteristics and environmental factors on soil nutrient loss in runoff plots. Our study provides a basis for a deeper understanding of the underlying mechanisms of soil loss and non-point source pollution. These direct and indirect effects require further studies determining the involved underlying processes, which play a crucial role in the optimization of soil erosion and nutrient loss management strategies.

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